NUTRIENT UPTAKE

Nutrient Uptake by Warm-Season Perennial Grasses in a Swine Effluent Spray Field

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ABSTRACT

Haying removes soil nutrients in manured fields. Grass hays were compared for nutrient removal in an effluent spray field. Eastern gamagrass (*Tripsacum dactyloides* L.), indiangrass [*Sorghastrum nutans* (L.) Nash], johnsongrass [*Sorghum halepense* (L.) Pers.], switchgrass (*Panicum virgatum* L.), and common and 'Coastal' bermudagrass [*Cynodon dactylon* (L.) Pers.] were grown on a Brooksville silty clay (fine, montmorillonitic, thermic Aquic Chromuderts) in Mississippi. The field produced johnsongrass hay and received swine (*Sus scrofa domesticus*) effluent (estimated 371, 61, and 629 kg ha^{-1} yr^{-1} of N, P, and K, respectively) for 8 yr before the study. In the 3-yr study, common bermudagrass produced 4.6 to 15.0 Mg dry matter (DM) ha^{-1} yr^{-1} and was not different from Coastal bermudagrass (5.2 to 13.7 Mg ha^{-1} yr^{-1}). Highest annual DM yields of johnsongrass, eastern gamagrass, switchgrass, and indiangrass were 9.7, 9.5, 9.1, and 5.5 Mg ha^{-1} yr^{-1}, respectively. Highest annual uptakes of N by common and Coastal bermudagrass, johnsongrass, eastern gamagrass, switchgrass, and indiangrass were 314, 280, 188, 181, 167, and 106 kg ha^{-1}, respectively. Respective highest annual uptakes of P were 44, 35, 23, 21, 19, and 14 kg ha^{-1}. Uptakes of Ca, K, Mg, Cu, Fe, Mn, and Zn were as high or higher in common bermudagrass as in the other grasses. Dry matter yield of common bermudagrass was correlated ($r = 0.99$, $P = 0.0001$) with uptakes of N, P, and K. Replacing johnsongrass with bermudagrass would increase annual DM yield in the field 155 to 249% and P uptake 194 to 259%.

W ITH INCREASING EMPHASIS on regulating land application of manures according to soil P levels, often referred to as the P index (Mallarino et al., 2002), characterization of the relative capacities of crop plants for removing P and other nutrients in high-P soils has become more important. The need for better utilization of nutrients in heavily manured soils has focused research on forage crops (Sims and Wolf, 1994). In the southeastern USA, bermudagrass responds well to the high levels of fertility found in swine effluent and consequently receives more effluent than any other warm-season perennial forage. Coastal bermudagrass receiving 670 kg N ha^{-1} and 153 kg P ha^{-1} from swine effluent removed an average of 382 kg N ha^{-1} yr^{-1} and 43 kg P ha^{-1} yr^{-1} (Burns et al., 1985). 'Alicia' bermudagrass responded to increasing levels of effluent by increased DM production and P uptake, up to a fertilizer N equivalent of 448 kg ha^{-1} (Adeli and Varco, 2001), but higher levels of effluent N produced no further increases in

DM. The efficiency of nutrient recovery in forage, as a percentage of nutrient applied in effluent, also declined with increasing rates of effluent fertilization for 'Russell' bermudagrass (Liu et al., 1997). A similar threshold on forage growth, with relatively little effect of N rates above 450 kg ha^{-1}, has also been reported for dairy manure (Macoon et al., 2002). Even with good N utilization by crops, long-term application of manure can result in soil enrichment in other nutrients, such as Ca, K, Mg, and P (Hao and Chang, 2003; Simard et al., 1995).

Nutrient uptake is primarily a function of plant biomass but may also vary due to differences in cultivars, weather, soil properties, and management practices (Robinson, 1996). Brink et al. (2003) found that differences in nutrient concentration produced P uptake per hectare in common bermudagrass equal to or greater than that of several hybrids, despite lower annual DM production by common bermudagrass.

Higher plants require N and P in ratios estimated at 6 to 10 (Sharpley and Halvorson, 1994). Adeli and Varco (2001) reported that the N/P ratio of swine effluent (which they collected in 1994–1996 on the same farm used in the present study) averaged 6.75. In that report, Adeli and Varco (2001) noted a range of N/P ratios in johnsongrass harvested from Okolona and Vaiden soils from 5.9 without effluent to "near 10" at the "high" level of effluent (665 and 94 kg ha^{-1} yr^{-1} of N and P, respectively). They reported that johnsongrass recovered 14 to 20% of applied P at this "high" level and 21 to 27% when a "medium" level of effluent was applied (462 and 62 kg ha^{-1} yr^{-1} of N and P, respectively). Adeli and Varco (2001) concluded that soil P accumulation would be expected in these soils for grasses with uptake ratios ≥ 10.

In subsequent experiments conducted on the same farm used by Adeli and Varco (2001), Brink et al. (2003) reported that effluent applied to a Brooksville soil in a spray field averaged 371 and 61 kg ha^{-1} yr^{-1} of N and P, respectively. The center-pivot–irrigated spray field and surrounding hay field were used for johnsongrass hay production. The rate of P accumulation in this spray field soil under johnsongrass haying can be estimated as 44.5 kg ha^{-1} yr^{-1}, using the P recovery rate (27%) reported for johnsongrass by Adeli and Varco (2001) and the P application rate (61 kg ha^{-1}) reported by Brink et al. (2003). This estimated accumulation rate is consistent with the P soil test level (99 mg kg^{-1} in the top 5 cm, or 222 kg ha^{-1}) observed by Brink et al. (2003) after 5 yr of effluent application to the spray field. Adeli et al. (2002) tested the effects of effluent applications

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Abbreviations: DM, dry matter.

on nutrient distribution in the soil profile of Vaiden silty clay (Hapludalfs) and Okalona silty clay (Chromuderts) soils on the farm described above and reported increased accumulation of K, Mg, P, and Zn in the upper 5 cm of soil and decreasing levels of these nutrients as soil depth increased. They also reported an absence of accumulations of these elements at soil depths below 15 cm. Accumulations of Ca, K, Mg, and P in the upper 15 cm of soil following long-term applications of swine effluent have also been reported for a Paleudult soil in the Coastal Plain of North Carolina, with P accumulation at 10 times the level above which no further response to P fertilization would be expected (King et al., 1990).

The objective of the present experiment was to compare the DM production, nutrient concentrations, and total nutrient removal of six warm-season perennial grasses harvested for hay from the spray field described above. The goal of the research was to find alternative warm-season perennial grasses, which might replace johnsongrass for improved forage production and nutrient removal, especially P, in the spray field. Common and Coastal bermudagrass were included in the test because of their wide usage in the southeastern USA. Three well-adapted native grasses (eastern gamagrass, indiangrass, and switchgrass) were also tested along with johnsongrass.

MATERIALS AND METHODS

The experiment was conducted on a private farm near Crawford in southwestern Lowndes County, Mississippi, USA (33°17′ N, 88°32′ W). Experimental plots were located in a swine effluent spray field, described earlier by Brink et al. (2003), on a Brooksville silty clay within the Blackland Prairie major land resource area. The spray field received anaerobic lagoon effluent and produced summer hay from a mixed grass stand dominated by johnsongrass. Amounts and timing of effluent applications were governed by the farm manager. Before the present study, effluent applications had been made to the spray field for 8 yr, and nutrient concentrations in the effluent had been monitored for 6 yr (Adeli and Varco, 2001; Brink et al., 2003). Effluent applied to the spray field had been monitored for 3 yr before the present study and averaged 371, 61, 629, 46, 0.61, 2.12, 30, 0.27, and 0.75 kg ha^{-1} yr^{-1} of N, P, K, Ca, Cu, Fe, Mg, Mn, and Zn, respectively (Brink et al., 2003). Soil test nutrient levels had also been measured in the plot area of the spray field 3 yr before the present study and showed 99, 620, 3, 74, 163, 83, and 2 mg kg^{-1} of P, K, Cu, Fe, Mg, Mn, and Zn, respectively, and 3.2 g kg^{-1} Ca in the top 5 cm of soil (Brink et al., 2003).

Below-normal rainfall during the fall and winter of 1999 and early spring of 2000 (Fig. 1) contributed to low water levels in the effluent lagoons and resulted in fewer effluent applications during the 2000 growing season. Rainfall during the May through September growing season totaled 29.3 cm in 2000, or 59% of the 30-yr average precipitation during these 5 mo. Regular effluent applications (0.3 to 0.6 ha cm application^{-1}, one to three times per week from April through September) resumed in 2001. May through September precipitation in 2001 was near normal, representing 102% of the 30-yr average rainfall. Application of effluent was suspended throughout the 2002 growing season due to mechanical breakdown of the center-pivot irrigation system in the spray field, but rainfall was normal (May through September precipitation totaled 49.6 cm, or 99% of the 30-yr average).

Nutrient analyses of soil samples from the plots were completed in December 1999 (after grasses were planted and plots
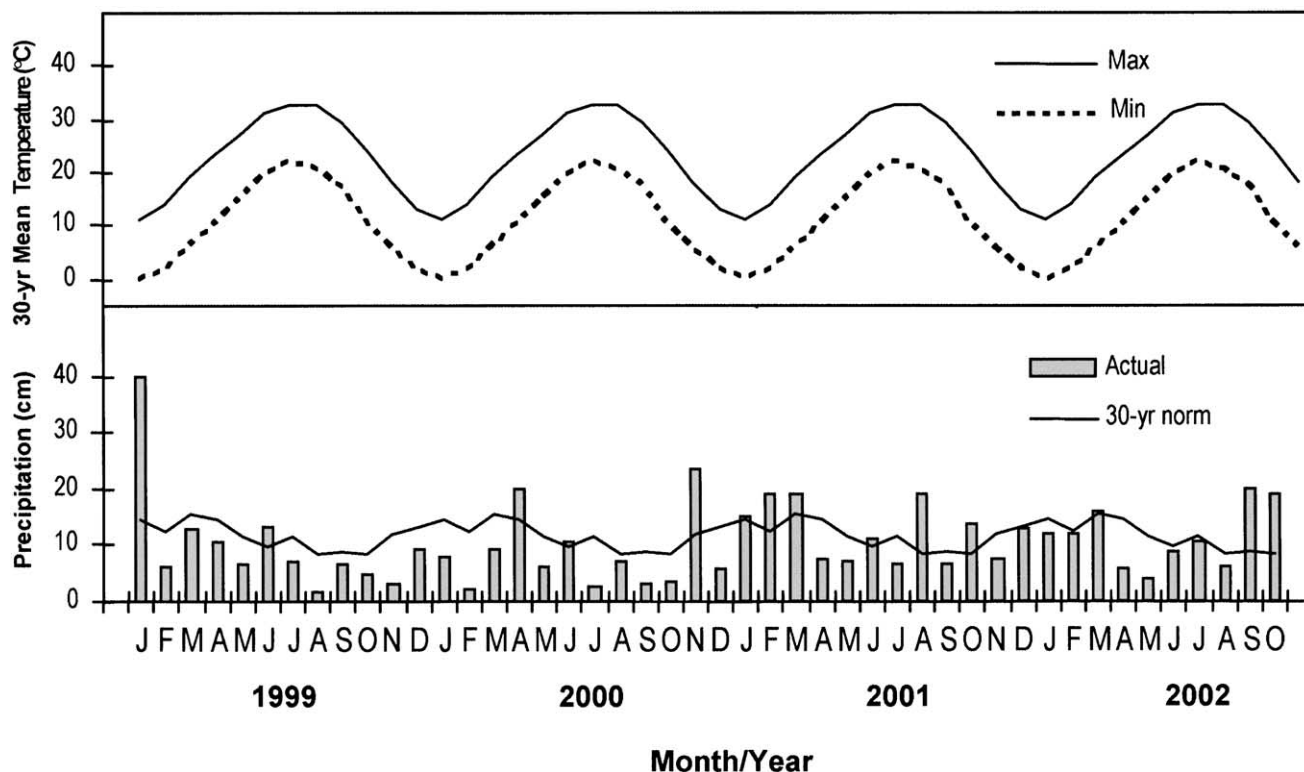

Fig. 1. Climatic conditions at the experimental plot site near Crawford, MS.

were established, but before hay harvests began), in December 2001 (after 2 yr of hay harvests), and in May 2003 (after 3 yr of hay harvests). In August 2003, soil samples were also collected, within the same soil-mapping unit of the hay field as the experimental plots, in an adjacent area, which was outside the center-pivot spray field and which had never received effluent. All soil samples were analyzed by the Mississippi State University Extension Service Soil Testing Laboratory using the Lancaster method (Cox, 2001), which is recommended for soils of the Black Belt (Blackland Prairie) (Adams and Mitchell, 2000). The soil test results confirmed that high levels of nutrients were present in the spray field soil before, during, and after the present study (Table 1). Levels of Mg, S, and Zn in the 2.5-cm soil surface layer were very high (greater than two times the optimum), and levels of Ca, K, and P were extremely high (greater than four times the optimum). Levels declined with increasing depth in the soil profile for all elements except Ca, which increased slightly, as did pH, in successively deeper samples. Soil collected outside the spray field showed markedly lower nutrient levels representative of the Brooksville soil, which had not received effluent (Table 1).

Experimental plots were 2 by 5 m and were surrounded by 2-m borders. Treatments consisted of the six grasses assigned to plots in a randomized complete block design with four replications. The plot area was prepared for no-till planting in 1999 by applications of glyphosate [isopropylamine salt of *N*–(phosphonomethyl)glycine] (2% applied with a backpack sprayer) to all except johnsongrass plots in April, May, and 1 wk before planting in June. The native species—eastern gamagrass, indiangrass, and switchgrass—were started from seed in *cone-tainers* (3.8-cm diam. by 21-cm length obtained from Stuewe & Sons, Corvallis, OR) in the greenhouse and transplanted in early July 1999 (40 plants per 10-m^2 plot on a 50-cm grid). Stratified seed of eastern gamagrass was supplied by Shepherd Farms, Clifton Hill, MO. Seed of indiangrass and switchgrass were supplied by Browning Seed, Plainview, TX. Plants were spaced for rapid growth and ground cover to enhance natural weed control. Bermudagrass plants were started from cuttings in the greenhouse and transplanted in late June (120 plants per 10-m^2 plot on a 25-cm grid). Existing johnsongrass stands in the surrounding area were used as a source of transplants for that species. Johnsongrass crowns with attached rhizomes and new shoots were transplanted at the same time as the native species. Below-

normal rainfall occurred in 1999, but above-normal rainfall and weekly effluent applications (0.3 to 0.6 ha cm application^{-1}, one to two times per week) during transplanting in June provided adequate soil moisture for successful establishment of all grasses. Plots were undisturbed in winter, except for burning accumulated thatch and stubble in February 2002. Broadleaf weeds were controlled with single applications of 2,4-D [(2,4–dichlorophenoxy) acetic acid] (66 mL of 10% active ingredient L^{-1} water, applied using a backpack sprayer) in August 1999 and March and July 2000. Alleys and borders were treated with glyphosate as needed for weed control and to prevent spreading of bermudagrass between plots.

Bermudagrass plants were clipped at a 2.5-cm stubble height monthly, beginning 4 wk after transplanting, to encourage prostrate stolon growth and rapid ground coverage for better weed control during establishment in 1999. Other species were clipped at 18 cm with a sickle-bar mower twice during the summer of 1999 to aid grassy weed control. Grasses were harvested for hay on 25 May (bermudagrass only), 7 July, and 29 Aug. 2000; 15 May, 19 June (except indiangrass), 3 Aug., and 28 Sept. 2001; and 27 May, 2 Aug., and 12 Sept. 2002. Bermudagrass was harvested at a cutting height of 2.5 cm, johnsongrass at 10 cm, and the other species at 20 cm using a sickle-bar mower. Fresh weight yields were recorded, and 1-kg samples were dried at 65°C for 72 h, weighed to determine DM yields for each plot and harvest, and ground to pass a 1-mm screen. Subsamples (50 g each) for subsequent nutrient analysis of the ground forage were stored at room temperature in sealed plastic amber-color vials. Total N concentration was determined by the macro-Kjeldahl procedure (Bremner, 1996). For each subsample, Ca, Cu, Fe, K, Mg, Mn, P, and Zn concentrations were measured using an inductively coupled argon plasma emission spectrophotometer following methods described by Brink et al. (2001). Nutrient uptake was calculated as the product of the nutrient concentration and DM yield for each plot and harvest.

Dry matter yield, nutrient concentration, and uptake data for each harvest were combined by growing season. Nutrient concentration means, total DM yields, and total nutrient uptake in each year were calculated for each plot and used in analysis of variance (ANOVA) (SAS Inst., 1990). Means were compared by Fisher's protected least significant difference (LSD, *P* = 0.05). Unless noted otherwise, the 0.05 level of probability was used to identify differences. Repeated-mea-

Table 1. Hay field soil test properties and nutrient levels of the Brooksville soil near Crawford, MS, inside the swine effluent spray field before (Dec. 1999), during (Dec. 2001), and after (May 2003) the experiment and in an adjacent area outside the spray field (Aug. 2003).

Sampling date	Sample depth	pH	OM†	CEC‡	P	K	Ca	Mg	S	Zn
	cm		g kg^{-1}	cmol kg^{-1}			mg kg^{-1}			
				Inside spray field						
Dec. 1999	0–2.5	7.2	59	31.0	274	1222	5109	280	425	2.6
	2.5–5	7.6	42	30.4	152	951	5244	209	299	1.4
	5–10	7.9	28	30.5	69	689	5505	148	203	0.8
	10–20	8.0	20	31.8	22	361	6060	73	141	0.5
Dec. 2001	0–2.5	7.6	43	26.5	231	1508	4098	261	310	4.1
	2.5–5	7.7	28	26.4	142	1192	4344	198	205	2.9
	5–10	7.9	20	25.7	74	891	4450	142	144	2.5
	10–20	8.2	15	27.8	34	471	5201	76	109	2.4
May 2003	0–2.5	6.9	58	30.1	224	1558	4434	265	419	3.7
	2.5–5	7.2	33	28.5	122	1071	4689	218	239	1.2
	5–10	7.5	26	27.4	75	913	4730	166	184	0.8
	10–20	8.0	17	27.8	22	541	5137	81	123	0.5
				Outside spray field						
Aug. 2003	0–2.5	5.5	25	18.2	13	151	1802	122	182	1.2
	2.5–5	5.3	24	19.1	9	107	1803	100	174	0.6
	5–10	5.3	18	17.5	7	78	1489	75	126	0.4
	10–20	5.5	9	18.1	5	67	1446	63	67	0.4

† OM, organic matter.
‡ CEC, cation exchange capacity.

sures analysis for years revealed a grass × year interaction; therefore, data were analyzed within years to test for differences among grasses and within grasses to test for differences among years. Correlation coefficients describing relationships of DM yields to nutrient uptakes for each grass were determined by correlation analysis (SAS Inst., 1990) of annual plot means for the 3-yr study.

RESULTS AND DISCUSSION

Dry Matter Yield

Dry matter yields by Coastal bermudagrass ranged from 5.24 to 13.71 Mg ha^{-1} yr^{-1} during the study (Table 2). Annual DM yields of Coastal bermudagrass were higher than those of the other species in all three growing seasons but were not different from those of common bermudagrass in 2000 and 2001. Mean DM yield of common bermudagrass ranged from 4.56 to 15.04 Mg ha^{-1} yr^{-1}. The DM production by bermudagrass in this study was lower than that reported for Coastal bermudagrass (22.4 Mg ha^{-1}) by Follett and Wilkinson (1985), but yields in 2001 were within the range of DM means (11.1 to 17.2 Mg ha^{-1} yr^{-1}) reported by Burns et al. (1990) for Coastal bermudagrass fertilized with low (335 kg N ha^{-1} yr^{-1}) to high (1340 kg N ha^{-1} yr^{-1}) loading rates of swine effluent over 11 seasons. The DM production in the present study was also within the range reported for bermudagrass on different soils fertilized with beef cattle feedyard effluent (Miller et al., 2001). Correlation analysis of DM yields and nutrient uptakes combined across all 3 yr showed very high correlations ($r = 0.99$, $P = 0.0001$) between DM yield and uptakes of N, P, and K in common bermudagrass.

The only grass to approach the DM production level of bermudagrass was switchgrass in 2000 when its mean DM yield of 4.66 Mg ha^{-1} was not different from either bermudagrass variety (Table 2). Dry matter production by eastern gamagrass and switchgrass was not different from that of johnsongrass, the predominant forage in the surrounding hay field. Dry matter yields of switchgrass in the present study (4.37 to 9.09 Mg ha^{-1} yr^{-1}) were lower than yields obtained from single-cut harvests reported by others (10.7 to 22.0 Mg ha^{-1} yr^{-1}) (Sanderson et al., 1999; Muir et al., 2001). Sanderson et al. (1999) concluded that more frequent harvests reduced yields of Alamo switchgrass, so it is possible that if the switchgrass in the present study had been managed for a single harvest, total DM may have been greater. The effect of cutting frequency on nutrient uptake in switchgrass is unknown and should be investigated.

Adequate rainfall and regular effluent applications in 2001 appeared to have a stimulating effect by increasing DM production of all grasses in the study. The greatest change came from eastern gamagrass, which increased 753% from 2000 to 2001. Relative increases by other grasses were johnsongrass, 283%; common bermudagrass, 230%; indiangrass, 216%; Coastal bermudagrass, 162%; and switchgrass, 95%. Lack of effluent application in 2002, even with near-normal rainfall, resulted in decreased DM production by all grasses, probably because of reduced N fertilization, which normally averaged 371 kg ha^{-1} (Brink et al., 2003). Relative decreases in DM production in 2002 compared with 2001 were johnsongrass, 80%; common bermudagrass, 68%; eastern gamagrass, 61%; Coastal bermudagrass, 55%; switchgrass, 52%; and indiangrass, 41%.

Nitrogen and Phosphorus Uptake

Both bermudagrass varieties had higher N and P uptakes than the other grasses (Tables 3 and 4). Uptake of N ranged from 72 to 314 kg ha^{-1} yr^{-1} in common bermudagrass and 78 to 280 kg ha^{-1} yr^{-1} in Coastal bermudagrass. Uptake of P ranged from 10.1 to 43.8 kg ha^{-1} yr^{-1} in common bermudagrass and 9.7 to 34.8 kg ha^{-1} yr^{-1} in Coastal bermudagrass. These annual uptake values are less than those reported for Coastal bermudagrass by Follett and Wilkinson (1985) (560 kg N ha^{-1} and 68.3 kg P ha^{-1}) and less than the 11-yr means reported for Coastal bermudagrass by Burns et al. (1990) (466 kg N ha^{-1} and 65 kg P ha^{-1}). Miller et al. (2001) reported P uptake by bermudagrass of 114 and 41 kg ha^{-1} on Pullman clay loam (Torrertic Paleustolls) and Amarillo fine sandy loam (Aridic Paleustalfs) soils, respectively, following fertilization with high rates of beef cattle feedyard effluent (500 kg N ha^{-1} yr^{-1} in 19.4-cm effluent). Lower uptake in the present study may be partially due to different soil type but is probably a result of low rainfall in 1999 and 2000 and reduced effluent applications (less effluent N) in 2000 and 2002.

The impact of reduced effluent applications was likely due to combined effects of reduced effluent water and

Table 2. Dry matter production of warm-season perennial grasses grown in a swine effluent spray field.

Grass	2000	2001	2002	LSD (0.05)
		Mg ha^{-1}		
Bermudagrass common	4.56	15.04	4.85	1.95
Bermudagrass 'Coastal'	5.24	13.71	6.12	1.08
Eastern gamagrass 'PMK-24'	1.11	9.47	3.70	0.86
Indiangrass 'Lometa'	1.75	5.53	3.29	1.33
Johnsongrass	2.53	9.70	1.95	1.79
Switchgrass 'Alamo'	4.66	9.09	4.37	1.04
LSD (0.05)	1.45	1.83	1.15	

Table 3. Nitrogen concentration and uptake of warm-season perennial grasses grown in a swine effluent spray field.

Grass	N concentration				N uptake			
	2000	2001	2002	LSD (0.05)	2000	2001	2002	LSD (0.05)
		g kg^{-1}				kg ha^{-1}		
Bermudagrass common	16.1	20.8	14.6	0.9	74.6	314.0	71.6	50.2
Bermudagrass 'Coastal'	16.8	20.4	12.7	1.9	87.8	279.7	78.0	31.7
Eastern gamagrass 'PMK-24'	16.7	19.0	14.4	1.7	18.6	180.6	53.6	26.0
Indiangrass 'Lometa'	12.8	19.4	12.7	1.9	22.2	105.8	41.4	20.3
Johnsongrass	14.1	19.3	17.1	3.8	34.1	187.8	32.3	37.0
Switchgrass 'Alamo'	11.7	18.4	12.3	1.4	54.4	167.0	53.5	19.3
LSD (0.05)	1.6	1.6	1.5		20.4	37.2	16.8	

Table 4. Phosphorus concentration and uptake of warm-season perennial grasses grown in a swine effluent spray field.

Grass	P concentration				P uptake			
	2000	2001	2002	LSD (0.05)	2000	2001	2002	LSD (0.05)
	g kg^{-1}				kg ha^{-1}			
Bermudagrass common	2.2	2.9	3.0	0.3	10.1	43.8	14.2	5.2
Bermudagrass 'Coastal'	1.9	2.6	2.7	0.2	9.7	34.8	16.7	4.2
Eastern gamagrass 'PMK-24'	1.8	2.2	2.2	0.2	2.0	20.8	8.0	2.3
Indiangrass 'Lometa'	1.7	2.6	2.2	0.4	3.0	14.4	7.3	3.3
Johnsongrass	1.6	2.3	2.9	0.5	3.9	22.6	5.7	4.0
Switchgrass 'Alamo'	1.4	2.2	2.0	0.2	6.4	19.4	8.5	2.2
LSD (0.05)	0.3	0.2	0.3		2.7	4.6	3.0	

reduced effluent N. Soil water has been shown to be the principal factor limiting wheat (*Triticum aestivum* L.) yield response to N under Mediterranean climatic conditions (Garabet et al., 1998; Lopez-Bellido and Lopez-Bellido, 2001). Wen et al. (2003) reviewed the losses of manure N in soils and found in the year following manure application that N physiological efficiency of wheat was higher with better available soil water. They also found a positive correlation between increase rate of manure N and wheat yield. Adeli et al. (2003) found higher yields of bermudagrass following swine effluent application in a wet year (123% of 30-yr average rainfall for April through November) than in a dry year (64% of 30-yr average rainfall for April through November). Linear regression analysis ($y = mx + b$) of the Adeli et al. (2003) data for N applied (x, kg ha^{-1}) and DM yield (y, kg ha^{-1}) of bermudagrass also showed a higher slope ($m = 10.8$) in the dry year than in the wet year ($m = 6.3$), indicating that as amounts of applied N decreased, DM yield decreased faster in the dry year than in the wet year.

Processes that affect the losses of manure N applied to soil include volatilization, erosion, leaching, immobilization, nitrification, and denitrification. Volatilization and losses of up to 70% of NH$_4$–N in effluent may occur during and immediately following sprinkler application (Al-Kaisi and Waskom, 2002). Immobilization, or loss of plant-available N, occurs as N is incorporated into the organic N pool in soil. Further losses due to denitrification and conversion of NO$_3$–N to volatile N$_2$O or N$_2$ may continue in soil, especially if organic matter is high, soil becomes waterlogged, and temperatures increase. Pu et al. (2001) found rainfall was the dominant factor controlling denitrification. Nitrification from decomposition of organic matter, or conversion of NH$_4$–N to NO$_3$–N, may make N more available to plants but also increases the potential for loss through leaching (Liu et al., 2003) and movement into groundwater (King et al., 1990). The relative low permeability of the Brooksville soil in the spray field may have favored reduced losses through leaching while the presence of permanent grass cover may have precluded significant losses through erosion; therefore, the major processes believed responsible for N losses in the absence of regular effluent applications were immobilization and denitrification.

Concentrations of P increased in all grasses in 2001 and 2002 compared with 2000 but did not differ between 2001 and 2002, except in johnsongrass where P concentration increased slightly in 2002 (Table 4). Johnsongrass had N and P concentrations in 2002 (17.1 g N kg^{-1} and

2.9 g P kg^{-1}, respectively) that were equal to or greater than those of bermudagrass, but higher DM yields by the bermudagrass resulted in greater N and P uptake than johnsongrass. Concentrations of P were higher in common bermudagrass than in other species, except for johnsongrass in 2002, and were also higher than in Coastal bermudagrass in 2001. These results confirmed earlier reports of Brink et al. (2000, 2003) that the annual P uptake of common bermudagrass equaled or exceeded that of bermudagrass hybrids fertilized with swine effluent in the same environment.

Adeli and Varco (2001) analyzed N and P concentrations in johnsongrass grown on an Okolona soil fertilized with swine effluent and reported concentrations ranging from 13.8 to 26.7 g N kg^{-1} and 1.9 to 2.8 g P kg^{-1} in the first and third treatment years. Uptake values for johnsongrass were calculated from the data of Adeli and Varco (2001) using their published regression equations for low (150 kg N ha^{-1} and 208 kg P ha^{-1}; 3-yr mean) and high (426 kg N ha^{-1} and 58 kg P ha^{-1}; 3-yr mean) effluent loading rates. These calculated uptakes
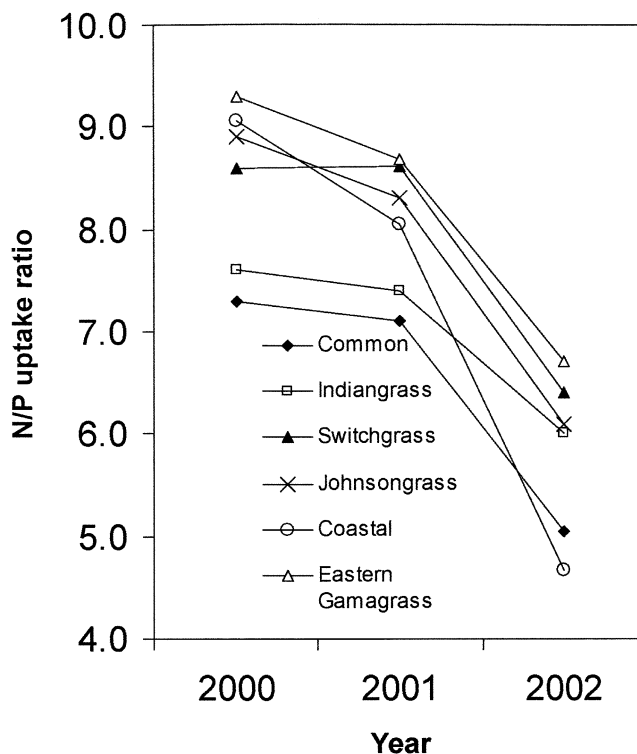

Fig. 2. Nitrogen/phosphorus uptake ratios of warm-season grasses grown in a swine effluent spray field near Crawford, MS, in 2000 (LSD 0.05 = 1.0), 2001 (LSD 0.05 = 0.5), and 2002 (LSD 0.05 = 0.7).

Table 5. Calcium concentration and uptake of warm-season perennial grasses grown in a swine effluent spray field.

Grass	Ca concentration				Ca uptake			
	2000	2001	2002	LSD (0.05)	2000	2001	2002	LSD (0.05)
	g kg^{-1}				kg ha^{-1}			
Bermudagrass common	4.6	4.9	5.7	0.3	21.0	74.6	27.5	14.2
Bermudagrass 'Coastal'	4.7	4.8	4.6	NS†	24.4	65.7	28.1	9.8
Eastern gamagrass 'PMK-24'	5.4	2.9	2.8	1.0	6.0	26.8	10.2	3.5
Indiangrass 'Lometa'	5.6	5.5	5.0	NS	9.4	31.4	16.5	12.8
Johnsongrass	4.9	4.3	5.0	NS	12.1	41.0	9.8	5.9
Switchgrass 'Alamo'	4.4	3.9	3.9	NS	20.7	34.8	17.2	6.6
LSD (0.05)	NS	1.0	0.5		7.5	15.9	6.5	

† NS, nonsignificant.

ranged from 152.2 to 227.5 kg N ha^{-1} and 17.8 to 24.8 kg P ha^{-1}. Values of N and P uptake by johnsongrass in 2001 of the present study, when rainfall and effluent applications were near normal, were 187.8 kg N ha^{-1} and 22.6 kg P ha^{-1} and were within the ranges calculated from the data of Adeli and Varco (2001).

Stout and Jung (1995) reported mean accumulation rates for biomass (203 kg ha^{-1} d^{-1}) and total N (2.45 kg ha^{-1} d^{-1}) of 'Cave-n-Rock' switchgrass across four soil types and 3 yr following a single application of 84 kg N ha^{-1} (as ammonium nitrate). Accumulations of Cave-n-Rock were 9.3 Mg DM ha^{-1} yr^{-1} and 112.7 kg N ha^{-1} yr^{-1} (Stout and Jung, 1995) compared with 9.1 Mg DM ha^{-1} and 167 kg N ha^{-1} for Alamo in 2001 of the present study. The N concentration of Alamo in 2001 of the present study (18.4 g kg^{-1}) was higher than the mean of Cave-n-Rock (12.1 g kg^{-1}) as calculated from the accumulation rates reported by Stout and Jung (1995).

Annual N/P uptake ratios for the six grasses ranged from 4.7 for Coastal bermudagrass in 2002 to 9.3 for eastern gamagrass in 2000 (Fig. 2). Ratios varied among years, probably influenced by changes in rainfall and effluent applications. Ranking of the grasses within years showed common bermudagrass ranked lower, except for Coastal bermudagrass in 2002, and eastern gamagrass ranked higher than the other grasses. Adeli and Varco (2001) reported an N/P ratio of 10.0 as the threshold for efficient removal (nutrients removed ≈ nutrients added) of N and P in a swine waste nutrient management hay system. When the objective in such a system is to provide adequate N for optimum forage production, while avoiding accumulation of excess P in the soil, forages with ratios < 10.0 are expected to satisfy the objective, but forages with ratios > 10.0 are not. The N/P ratios of all grasses in the present study were <10.0, with common bermudagrass and indiangrass displaying the lowest (most efficient) ratios (Fig. 2). Com-

parison of N/P uptake ratios among grasses in 2000 and 2001 showed their relative responses to effluent application and high soil nutrient levels while comparisons of ratios in 2002, when no effluent was applied, revealed their relative responses to high soil nutrient supply only (Fig. 2).

Based on 3-yr means for DM yield and P uptake from this study, replacing johnsongrass with common bermudagrass in this spray field would increase annual DM yield 172% and increase annual P removal 212%. With normal rainfall and effluent applications, these increases would be expected to be even greater. Nevertheless, even at the highest level of P removal recorded here, 44 kg ha^{-1} for common bermudagrass in 2001 (Table 4), with annual effluent P additions estimated at 61 kg ha^{-1} (Brink et al., 2003), P accumulation would be expected to continue at the rate of 17 kg ha^{-1}yr^{-1}. Additional P removal, such as provided by spring hay production from overseeding bermudagrass with cool-season winter annual berseem clover (*Trifolium alexandrinum* L.) (McLaughlin et al., 2001), is needed to balance P input in this spray field soil.

Other Macronutrients

Uptake of Ca was greater by bermudagrass than all other grasses in all three growing seasons, except for switchgrass in 2000 (Table 5). Common and Coastal bermudagrass did not differ in Ca uptake and ranged from 21.0 to 74.6 kg ha^{-1} yr^{-1} over the 3 yr. The Ca concentrations among the six grasses did not differ in 2000, but in 2001 and 2002, concentrations in common bermudagrass were consistently high while those in eastern gamagrass were consistently low (Table 5).

Uptake of K by Coastal bermudagrass was greater than other grasses in all 3 yr, except for common bermudagrass in 2000 and 2001 and switchgrass in 2002 (Table 6). Potas-

Table 6. Potassium concentration and uptake of warm-season perennial grasses grown in a swine effluent spray field.

Grass	K concentration				K uptake			
	2000	2001	2002	LSD (0.05)	2000	2001	2002	LSD (0.05)
	g kg^{-1}				kg ha^{-1}			
Bermudagrass common	17.3	24.5	15.8	1.5	80.2	369.3	77.9	56.1
Bermudagrass 'Coastal'	19.2	26.5	17.2	1.5	100.7	363.8	105.6	40.4
Eastern gamagrass 'PMK-24'	15.5	23.6	21.6	2.1	17.4	223.9	80.0	24.2
Indiangrass 'Lometa'	15.8	24.4	19.9	2.2	27.8	132.7	64.5	25.8
Johnsongrass	14.0	26.5	24.2	2.1	35.7	258.1	46.9	50.5
Switchgrass 'Alamo'	16.3	25.7	20.1	2.2	75.0	234.0	87.9	25.4
LSD (0.05)	1.8	2.0	2.3		25.3	47.4	23.8	

Table 7. Magnesium concentration and uptake of warm-season perennial grasses grown in a swine effluent spray field.

Grass	Mg concentration				Mg uptake			
	2000	2001	2002	LSD (0.05)	2000	2001	2002	LSD (0.05)
	g kg^{-1}				kg ha^{-1}			
Bermudagrass common	0.75	1.12	0.68	0.10	3.5	17.2	3.5	4.0
Bermudagrass 'Coastal'	0.78	1.15	0.63	0.19	4.1	15.8	3.8	3.4
Eastern gamagrass 'PMK-24'	0.68	0.80	0.53	0.06	0.7	7.4	1.9	0.7
Indiangrass 'Lometa'	0.53	0.93	0.65	0.15	0.9	5.3	2.0	1.5
Johnsongrass	0.58	1.13	1.13	0.16	1.5	11.1	2.2	1.9
Switchgrass 'Alamo'	0.93	1.28	0.93	0.15	4.3	11.6	4.1	1.8
LSD (0.05)	0.14	0.13	0.16		1.2	3.4	1.0	

sium uptake by common bermudagrass ranged from 77.9 to 369.3 kg ha^{-1} yr^{-1}, and uptake by Coastal bermudagrass ranged from 100.7 to 363.8 kg ha^{-1} yr^{-1}. Differences in K concentrations were observed among grasses in each year (Table 6). Differences between highest and lowest K concentrations were 5.2 g kg^{-1} in 2000 when some effluent was applied and rainfall was below normal, 2.9 g kg^{-1} in 2001 when effluent applications and rainfall were normal, and 8.4 g kg^{-1} in 2002 when no effluent was applied and rainfall was normal. The K concentrations in the bermudagrass varieties ranked at or near the highest of the grasses in 2000 and 2001 but lowest in 2002 (Table 6), suggesting a relatively greater response to effluent-applied K in bermudagrass than in the other grasses despite high levels of K in the soil (Table 1). The K concentrations in johnsongrass, however, ranked lowest in 2000 and highest in 2001 and 2002, suggesting a relatively greater response to rainfall, soil moisture, and soil-supplied K by johnsongrass than by the other grasses.

Uptake of Mg was also greater by bermudagrass than other grasses in all 3 yr, except for switchgrass in 2000 and 2002 (Table 7). The concentration of Mg in switchgrass was equal to or higher than the other grasses except for johnsongrass in 2002 (Table 7). Uptakes of Mg ranged from 3.5 to 17.2 kg ha^{-1} yr^{-1} for common bermudagrass and 3.8 to 15.8 kg ha^{-1} yr^{-1} for Coastal bermudagrass and were not different. Uptake of Mg by switchgrass ranged from 4.1 to 11.6 kg ha^{-1} yr^{-1}.

Forages with Mg concentrations of less than 2 g kg^{-1} and K concentrations of more than 30 g kg^{-1} or with K/(Ca + Mg) ratios (on a cmol$_c$ kg^{-1} basis) greater than 2.2 have been associated with grass tetany in grazing animals (Grunes and Welch, 1989). The Mg concentrations measured in the present study were all less than 2 g kg^{-1}, and the respective K concentrations were all less than 30 g kg^{-1}. The K/(Ca + Mg) ratios (Table 8)

Table 8. Cation equivalent ratios of grass forages grown in a swine effluent spray field.

Grass	2000	2001	2002	LSD (0.05)
	K/(Ca + Mg)			
Bermudagrass common	1.6†	1.9	1.2	0.2
Bermudagrass 'Coastal'	1.7	2.0	1.6	0.2
Eastern gamagrass 'PMK–24'	1.3	2.9	3.1	0.4
Indiangrass 'Lometa'	1.3	1.8	1.7	0.4
Johnsongrass	1.3	2.3	1.8	0.3
Switchgrass 'Alamo'	1.5	2.2	1.9	0.3
LSD (0.05)	NS‡	0.4	0.2	

† cmol$_c$ kg^{-1} basis.
‡ NS, nonsignificant.

were equal or below the 2.2 threshold for grass tetany for all grasses in all years, except for eastern gamagrass in 2001 and 2002. Ratios for eastern gamagrass in those years were 2.9 and 3.1, respectively. The K/(Ca + Mg) ratio for eastern gamagrass was 1.3 in 2000. Eastern gamagrass has not been linked with grass tetany in forage literature, but the potential for grass tetany problems from feeding this forage following heavy fertilization with swine effluent has not been investigated. Burns et al. (1987) also recognized a potential hazard from swine effluent–fertilized temperate forage grasses. Other studies have shown that increasing available P was associated with increased uptake of Ca and Mg in temperate forage grasses (Lock et al., 2002; Reinbott and Blevins, 1991, 1997), reducing the K/(Ca + Mg) ratio and tetany potential. Although grass tetany is considered a grazing problem and grazing effluent-treated forage is not a recommended practice, the effects of feeding ruminant animals with high K/(Ca + Mg) ratio hay of eastern gamagrass are unknown and should be investigated.

Micronutrients

Uptake of the micronutrients Cu, Fe, Mn, and Zn was generally as great or greater in Coastal bermudagrass as in the other grasses, except for Cu and Fe in 2002 (Tables 9–12). Uptake of Cu, Fe, and Mn by switchgrass was not different from that of Coastal bermudagrass in 2000. In 2001, the most favorable of the three growing seasons, uptake of Cu in bermudagrass was higher than in the other grasses due to increased DM yields by bermudagrass (Table 9). The Cu uptake by common bermudagrass (97.6 g ha^{-1}) and Coastal bermudagrass (95.8 g ha^{-1}) was not different in 2001 (Table 9). Concentrations of Cu increased in all grasses in 2001 compared with 2000, then declined in 2002. Copper concentrations in bermudagrass in 2002 were below those of 2000 while levels in the other grasses, although less than in 2001, were not different from levels in 2000. Since rainfall was below normal in 2000 and normal in 2001 and 2002 while effluent was applied irregularly (zero to two times per week) in 2000, regularly (two to three times per week) in 2001, and not at all in 2002, it appeared that bermudagrass, possibly due to its dense sod, formed by abundant shallow fibrous roots, stolons, and fine leaves, was more responsive to available Cu in effluent applications than were the other grasses.

Tissue Cu concentrations (Table 9) were lower than the average of 9 mg kg^{-1} reported by Burns et al. (1990) for Coastal bermudagrass fertilized with swine effluent,

Table 9. Copper concentration and uptake of warm-season perennial grasses grown in a swine effluent spray field.

Grass	Cu concentration				Cu uptake			
	2000	2001	2002	LSD (0.05)	2000	2001	2002	LSD (0.05)
	mg kg^{-1}				g ha^{-1}			
Bermudagrass common	3.7	6.4	2.6	1.1	16.6	97.6	13.1	22.4
Bermudagrass 'Coastal'	5.0	7.0	2.7	1.5	26.1	95.8	16.6	22.2
Eastern gamagrass 'PMK-24'	5.5	8.0	5.9	1.6	6.2	75.7	22.0	15.1
Indiangrass 'Lometa'	5.1	7.5	5.3	2.0	8.9	42.4	18.0	14.9
Johnsongrass	4.0	7.2	5.6	1.5	10.5	70.1	10.7	14.6
Switchgrass 'Alamo'	4.9	7.1	5.2	1.5	22.1	64.4	22.9	11.1
LSD (0.05)	0.9	1.1	1.5		7.0	17.7	8.9	

possibly due to differences in seasonal effluent loading rates. Studies of micronutrient uptake in 15 clipped turf bermudagrass cultivars under irrigation and monthly N and K fertilization (196 kg ha^{-1} yr^{-1} of N and K) showed Cu concentrations averaging 13.5 to 14.8 mg kg^{-1} (McCrimmon, 2000, 2002). Increased fertilizer N and K (343 kg ha^{-1} yr^{-1} of N and K) resulted in a higher average Cu concentration of 22.0 mg kg^{-1} in the turf bermudagrass cultivars (McCrimmon, 2002).

No differences in Fe concentrations were found among the six grasses, but Coastal bermudagrass, indiangrass, and switchgrass showed differences in Fe concentrations between years (Table 10). Tissue Fe concentrations were within the range of those reported for Coastal bermudagrass (average of 92 mg kg^{-1}) fertilized with swine effluent (Burns et al., 1990) but below those reported (166–260 mg kg^{-1}) for turf bermudagrass cultivars (McCrimmon, 2000, 2002).

Forage Mn concentrations (Table 11) were below the range of those reported for Coastal bermudagrass (25–325 mg kg^{-1}) (Mills and Jones, 1996) and turf cultivars (McCrimmon, 2000, 2002). Uptake of Mn was greater in bermudagrass than in johnsongrass in all 3 yr.

Forage Zn concentrations (Table 12) were less than the average of 33 mg kg^{-1} reported by Burns et al. (1990) for Coastal bermudagrass fertilized with swine effluent and also below those reported for heavily fertilized turf bermudagrass cultivars, which averaged 72 to 93 mg kg^{-1} (McCrimmon, 2000, 2002). Zinc concentrations in harvested forage in the present study increased from 2000 to 2002 in all grasses except indiangrass and appeared to be independent of yearly variations in effluent application. This trend was also observed in indiangrass, but with differences that were not statistically significant, and suggests possible adaptation by the grasses to high Zn levels in the soil.

CONCLUSIONS

In comparing the overall performance of the bermudagrass to the other grasses, there were 12 instances (four other grasses, 3 yr) for each of 19 parameters (DM, nine nutrient concentrations, nine nutrient uptakes) for a total of 228 possible instances when another grass could equal or exceed the measured performance of the bermudagrass. In this context, the performance of the bermudagrass exceeded those of the other four grasses 83% of the time in DM yield, 28% of the time in nutrient concentration, and 76% of the time in nutrient uptake. Plant nutrient uptake was generally increased for all grasses in 2001, a year of near-normal rainfall and effluent applications, compared with 2000, a year of reduced rainfall and effluent applications, and 2002, a year of normal rainfall and no effluent applications. The increased uptake in 2001 occurred despite the fact that nutrient levels in the soil were well above the optimums throughout the experiment and demonstrated plant responses to effluent supply despite high nutrient levels in soil. We propose that the additional effluent N supplied in 2001 increased DM yields and, as a consequence, P and other nutrient uptake.

The native well-adapted species (indiangrass, eastern gamagrass, and switchgrass) equaled or exceeded the performance of johnsongrass 89% of the time for DM yield, 72% of the time for nutrient concentration, and 91% of the time for nutrient uptake. With the possible exception of indiangrass, these native species could be used in the current nutrient management system as alternatives to johnsongrass; however, only switchgrass in 2000 and 2002 yielded as much DM as common bermudagrass. The performance of common bermudagrass equaled or exceeded that of Coastal bermudagrass in 2 out of 3 yr for DM production and 93% of the time for nutrient concentration and nutrient uptake. We con-

Table 10. Iron concentration and uptake of warm-season perennial grasses grown in a swine effluent spray field.

Grass	Fe concentration				Fe uptake			
	2000	2001	2002	LSD (0.05)	2000	2001	2002	LSD (0.05)
	mg kg^{-1}				g ha^{-1}			
Bermudagrass common	69	113	114	NS†	327	1708	636	664
Bermudagrass 'Coastal'	95	151	63	60	498	2122	384	998
Eastern gamagrass 'PMK-24'	131	113	78	NS	141	1062	288	186
Indiangrass 'Lometa'	139	83	88	39	235	457	295	80
Johnsongrass	89	106	71	NS	225	996	139	181
Switchgrass 'Alamo'	72	92	66	18	344	831	289	135
LSD (0.05)	NS	NS	NS		162	725	NS	

† NS, nonsignificant.

Table 11. Manganese concentration and uptake of warm-season perennial grasses grown in a swine effluent spray field.

Grass	Mn concentration				Mn uptake			
	2000	2001	2002	LSD (0.05)	2000	2001	2002	LSD (0.05)
	mg kg^{-1}				g ha^{-1}			
Bermudagrass common	20.2	23.6	15.7	2.9	92.4	360.3	78.7	88.0
Bermudagrass 'Coastal'	15.6	21.2	14.2	4.3	81.5	291.9	87.2	50.9
Eastern gamagrass 'PMK-24'	15.3	17.0	14.8	1.0	17.0	160.4	55.2	15.8
Indiangrass 'Lometa'	18.1	22.4	20.0	NS†	31.5	124.8	66.0	32.1
Johnsongrass	13.5	15.2	14.5	NS	35.0	145.5	28.4	21.2
Switchgrass 'Alamo'	17.0	20.1	14.0	1.8	79.2	182.9	61.0	30.3
LSD (0.05)	3.7	2.9	3.5		29.7	69.1	31.0	

† NS, nonsignificant.

Table 12. Zinc concentration and uptake of warm-season perennial grasses grown in a swine effluent spray field.

Grass	Zn concentration				Zn uptake			
	2000	2001	2002	LSD (0.05)	2000	2001	2002	LSD (0.05)
	mg kg^{-1}				g ha^{-1}			
Bermudagrass common	21.3	23.0	28.0	3.9	97.1	342.4	135.4	26.6
Bermudagrass 'Coastal'	19.8	20.7	26.7	3.6	103.7	282.8	163.6	50.4
Eastern gamagrass 'PMK-24'	13.2	16.9	18.1	2.2	14.7	160.0	66.6	21.3
Indiangrass 'Lometa'	19.9	22.3	23.4	NS†	35.3	124.8	79.4	35.7
Johnsongrass	14.3	15.8	26.8	7.2	36.6	151.9	54.5	37.0
Switchgrass 'Alamo'	12.5	14.7	19.4	2.5	57.3	134.1	84.9	13.6
LSD (0.05)	3.3	2.8	4.0		28.9	37.5	37.5	

† NS, nonsignificant.

clude that from among the six grasses tested, common bermudagrass is the best choice for replacing johnsongrass as a warm-season perennial grass hay crop for nutrient management in this swine effluent spray field.

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